The Aircraft Noise Simulation Working Group (ANSWr) – V-2 Aircraft Results

Laurent Sanders*, Russell H. Thomas†, Lothar Bertsch‡, Ingrid Legriffon*, Ian A. Clark†, Jason C. June† and Mathieu Lorteau*

A joint research activity of DLR, NASA and ONERA in the field of aircraft noise simulation is described. The Aircraft Noise Simulation Working Group (ANSWr) has been established to compare simulation tools, establish guidelines for noise prediction, assess uncertainties associated with the simulation, and establish a common knowledge in the field. These goals have been accomplished by using two virtual aircraft as a benchmark: a conventional tube-and-wing configuration as a reference case, and the low noise DLR configuration, V-2. The benchmark setup and results for the reference aircraft are presented in a separate paper. The purpose of the present paper is to describe the benchmark test case dealing with the V-2, a high wing aircraft concept with engines mounted above the wing and fuselage junction. The noise associated with this configuration is greatly dependent on the acoustic shielding of the engines by the airframe. Consequently, the comparison of the computed results focuses on the acoustic shielding calculations as well as on the noise source components. Remarkably, all three prediction methods show a good agreement with discrepancies typically lower than 4 dB for overall aircraft noise metrics such as peak noise levels. However, at forward and aft angles the aircraft system noise predicted can begin to show much larger differences, up to 5-10 dB. Much of the differences at large angles can be attributed to the shielding predictions but can also be due to some significant differences between the three predictions of the airframe noise sources.

Nomenclature

ANOPP	Aircraft NOise Prediction Program
CARMEN	Codes Acoustiques par Rayons pour la Modélisation et l'Estimation de Nuisances
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
IENTA	Infrastructure d'Evaluation de Systèmes de Transport Aérien (Infrastructure for Evaluating Air Transport Systems)
NASA	National Aeronautics and Space Administration
ONERA	Office National d'Etudes et de Recherches Aérospatiales
PANAM	Parametric Aircraft Noise Analysis Module

Variable	Name	Unit
SEL	sound exposure level	dB(A)
SPL	sound pressure level	dB
L _A	A-weighted overall sound pressure level	dB(A)

I. Introduction

Community annoyance caused by aircraft noise continues to be the major issue adversely affecting the growth of the global air transport system in numbers of airports, the expansion of existing airports, or the increased frequency

* ONERA – The French Aerospace Lab, F-92322 Châtillon, France.

† NASA Langley Research Center, Aeroacoustics Branch, 2 N. Dryden St., MS 461, Hampton, VA 23681, USA.

‡ DLR, Institute of Aerodynamics and Flow Technology, Bunsenstr. 10, 37073 Göttingen, Germany.

of flights. The increasing demand for more air travel coupled with increasing population density around major airports and along common air traffic routes could further negatively impact growth in the future.¹ Two general strategies have been identified to mitigate the impact of aircraft noise: (i) modification of the aircraft, i.e., modification of the noise sources, and (ii) modification of the flights, i.e., flight procedure and schedule. Aircraft noise prediction tools are required to quickly assess the impact of these modifications on the noise perceived on the ground.

Several years ago, DLR initiated the Aircraft Noise Simulation Working Group (ANSWr), which comprises three research organizations – DLR, NASA and ONERA – to establish a better common understanding of aircraft noise simulation based on their experience developing their own aircraft noise prediction tools. More precisely, several test cases were proposed and evaluated to aid in direct tool-to-tool comparison among the three codes PANAM,² ANOPP³ and CARMEN⁴ developed by DLR, NASA and ONERA, respectively. A complete description of this benchmark is given in Ref. 5.

For over a decade, there has been a growing interest in investigating innovative, unconventional aircraft architectures. One motivation for unconventional configurations is the potential acoustic benefit. For instance, the blended wing body showed significant noise reduction due to acoustic shielding⁶ of the dorsal integrated engines. Due to the potential impact of engine shielding, the DLR configuration V-2² was proposed as an ANSWr benchmark. This provides an opportunity to compare the acoustic shielding calculation – more generally the acoustic diffraction calculation – inside the whole computational chain of the aircraft noise simulations for each of the three tools. The V-2 configuration is a high wing aircraft design with a cylindrical fuselage. The engines are dorsal mounted and are shielded by the fuselage and wings. The comparison of the computational result produced with PANAM, ANOPP and CARMEN is expected to

- (i) increase the confidence in the implementation of the simulation processes,
- (ii) evaluate different approaches or computational implementations for noise shielding calculation, and
- (iii) aid in drawing guidelines for the acoustic diffraction calculation in the aircraft noise simulations.

The paper is organized as follows. The ANSWr test case selected for this study is first presented. Then, the three aircraft noise simulation tools used in this work are detailed. A focus on the acoustic shielding calculation method used in each toolset is also included. The last section is dedicated to a comparison of the results, as well as discussion.

II. ANSWr V-2 Aircraft Test Case

The V-2 aircraft (Figure 1) has been designed by DLR². The input data required for the noise prediction tools are the

- aircraft design and airframe parameters (e.g., landing gear wheel diameter), as well as a detailed CAD file required for the shielding calculation,
- engine design and performance parameters (e.g., fan diameter), and
- flight procedures (e.g., flight path, engine thrust).

These data have been created by DLR, and are based on the required input data for a PANAM noise prediction. Complete details and references can be found in Ref. 5.

Figure 1. V-2 aircraft concept².

The benchmark presented in this paper is composed of several test-case extracted from the ANSWr benchmark. Table 1 synthesizes the test-case of the V-R and V-2 aircraft, the V-R aircraft being the reference aircraft whose simulation results are presented in a companion paper⁵. The V-2 aircraft simulations – on which the present paper focuses – specifically include the acoustic shielding of the engine noise sources whereas the V-R aircraft simulations assume that no acoustic installation effects occur. For the first two simulations (#3-4), comparisons are made around the aircraft assuming static conditions. For the two following simulations (#7-8), simplified departure and approach

flight paths are flown with constant flight and engine conditions used in simulations #3-4. The last pair of simulations (#11-12) use variable flight and engine conditions for both a departure and approach flight path.

#	vehicle	type	output	simplifications
TC-1a: constant flight condition				
1	V-R	app.	3 emission spectra	no shielding, no lining, no ground attenuation
2	V-R	dep.	3 emission spectra	no shielding, no lining, no ground attenuation
3*	V-2	app.	3 emission spectra	no lining, no ground attenuation
4*	V-2	dep.	3 emission spectra	no lining, no ground attenuation
TC-1a: simplified flyover				
5	V-R	app.	tlh and integrated sound metrics (1 obs.)	no shielding, no reflection, no lining, no ground attenuation
6	V-R	dep.	tlh and integrated sound metrics (1 obs.)	no shielding, no reflection, no lining, no ground attenuation
7*	V-2	app.	tlh and integrated sound metrics (2 obs.)	no lining, no ground attenuation
8*	V-2	dep.	tlh and integrated sound metrics (2 obs.)	no lining, no ground attenuation
TC-1b: simulated flight				
9	V-R	app.	contour plot (SEL)	no shielding, no reflection, no lining, no ground attenuation
10	V-R	dep.	contour plot (SEL)	no shielding, no reflection, no lining, no ground attenuation
11*	V-2	app.	contour plot (SEL)	no lining, no ground attenuation
12*	V-2	dep.	contour plot (SEL)	no lining, no ground attenuation

Table 1. V-R and V-2 test-case defined in the ANSWr benchmark. Extracted from [5]. (*results presented in this paper)

Figure 2. V-2 geometry (without nacelles) and starboard engine source locations: point A is the fan center and point B is the jet bypass nozzle exit.

III. Aircraft Noise Simulation Tools

A. ANOPP

NASA has been continually developing an aircraft system noise prediction capability since the 1970s beginning with ANOPP.⁷ For more than ten years, both the noise prediction methods of ANOPP and the second generation framework, ANOPP2,³ continue to be developed specifically for the challenges of higher fidelity predictions and the

need for expanded capability to accurately predict future, advanced low-noise aircraft configurations^{8, 9} for which propulsion airframe aeroacoustic effects are critical.

The same prediction methods used for the companion case⁵ are applied here to compute the system noise of the V-2 aircraft with ANOPP. However, an additional prediction method is required to estimate the shielding of the engine sources by the airframe. NASA's method for scattering prediction follows the general approach for high frequency acoustics. The contributions to the diffracted field are calculated through an integration over a diffraction contour and can include both sharp and curved edges. The contributions from sharp edges are calculated by the classical theory of Kirchhoff integration and those from smooth curved edges are calculated by the theory of surface creeping wave diffraction.

For application to aircraft scattering, Lummer¹⁰ developed his method in 2008. Separately, Guo et al.¹¹ implemented a method based on the classical theory and published comparisons with canonical and experimental data. Since 2017, the NASA team has completely reformulated and recoded the method in a new research scattering code named Propulsion Airframe Aeroacoustic Scattering for System Noise (PAASSyN) that is unpublished.

The NASA prediction of noise shielding for the V-2 aircraft was performed with an early version of the PAASSyN code without the effect of mean flow. The shielding effects were predicted as a separate calculation outside of the ANOPP system noise prediction tool and the results are supplied to ANOPP as noise reduction delta SPLs. The shielding predictions were made separately for inlet radiated fan noise and for aft radiated engine noise. The latter was applied to aft fan noise and also to jet noise, while the former was applied only to forward fan noise. An arrangement of monopole sources (Figure 3) was distributed at the location of the nacelle face, i.e. slightly upstream of point A (cf. Figure 2), to simulate the engine noise sources. Both nacelles were included in the prediction. The predictions are made and applied at each one-third octave band from 50 Hz to 10 kHz.

Figure 3. Distributed sources locations in PAASSyN for ANOPP simulations.

B. PANAM

DLR activities in the field of noise source modeling can be found in the literature from the year 2000 onward.^{12, 13, 14} Since that point, noise source models for additional sources continue to be introduced, while older models have been developed further. Work has also been done to include and account for interaction effects. From 2008 on, the DLR noise source models have been implemented into an aircraft system noise simulation process.⁹ Since then, the corresponding simulation tool PANAM has been further improved and updated, e.g., to incorporate noise shielding effects and acoustic lining material. The noise shielding module in use by PANAM is also based on classical Kirchhoff integral theory and is implemented by Lummer.¹⁰

The analysis of Propulsion Airframe Aeroacoustic interaction effects is essential when investigating low-noise aircraft concepts¹⁵. Consequently, at DLR multiple simulation tools of varying fidelity are available. A ray tracing tool called SHADOW was specifically developed in order to investigate different engine installations with respect to noise shielding at low computational costs¹⁰. Due to its fast computation times and low input data requirements compared to higher fidelity approaches, the tool can directly be implemented within an aircraft design simulation process. It is possible to assess noise shielding for a large number of design iterations within a short time as it is commonly found in conceptual design studies. The tool has been applied in a large design study with approximately 500 vehicle variants that each have been simulated along individual approach and departure flights². The most promising vehicle concept from this 2013 study is the V-2 vehicle that is assessed within this benchmark test.

SHADOW is based on a high frequency approximation of the linearized Euler equations¹⁰. The pressure field is calculated by solving ordinary differential equations along rays in space. These rays originate in a point source, which approximates the selected noise source that is attenuated. Attenuation factors can be predicted for arbitrary

point sources, e.g., to assess the shielding of fan inlet and exhaust noise, but also to assess reflection of main landing gear noise if installed under a blended wing body. For a selected vehicle concept, frequency dependent noise attenuation factors are predicted with SHADOW and directly fed back into PANAM for further assessment of the vehicle system noise.

A local second-order polynomial geometry approximation is applied to take into account surface curvature, thus enable proper calculation of the ray reflection. The pressure amplitude along each ray is calculated based on energy conservation which requires the calculation of the Jacobian of the ray field. To compute acoustic shielding at arbitrary points in space, a shooting procedure based on a Newton algorithm is applied. In the high frequency limit the diffractive part of the solution of the wave equation is lost. This part of the solution could be approximated by the geometrical theory of diffraction which can be applied toward simple geometries. Yet an implementation for arbitrary geometries is complicated hence a more simple approach based on the Maggi-Rubinowicz formulation of the Kirchhoff diffraction theory has been implemented. The diffracted field is calculated by a line integral along the shadow boundary on the surface of the diffracting body. In contrast to the ray field, the diffraction correction is frequency dependent. Since only the acoustic far field is calculated in the implemented form of the high frequency approximation, it is sufficient to consider acoustic point sources¹⁰.

In the following calculations, referring to Figure 2, fan inlet and jet inlet noise sources are located at point A whereas fan outlet and jet outlet noise sources are located at point B.

C. CARMEN

For about 10 years, the system noise prediction tool CARMEN⁴ has been developed at ONERA within the Infrastructure for Evaluating Air Transport Systems¹⁶ (IESTA) – a platform dedicated to the environmental impact of the air traffic surrounding airports in terms of noise and chemical emissions. CARMEN is composed of three modules: the acoustic source module, the installation effects module and the atmospheric propagation module. Each of these modules is assessed against reference results from experiments, analytical solutions or simulations. Most of the noise source models are based on semi-empirical models derived from the literature. Prior to their implementation in CARMEN, these models have been assessed against experimental results obtained by ONERA⁴. The module for installation effects is based on either the ray model, which accounts for direct and reflected rays, as well as the diffraction by the whole aircraft geometry, or the boundary element method (BEM) which computes the acoustic field diffracted by the whole aircraft geometry. The atmospheric propagation module, also based on the ray model, includes the effects of wind, temperature gradients, and atmospheric absorption along the ray path. Finally, comparisons with flight test measurements^{17, 18, 19} validate the computational chain in CARMEN relying on the coupling of these three modules. During the CARMEN simulation, both static (aircraft geometry and meteorology) and dynamic variables (acoustical aircraft sources) relative to the trajectory are considered. To save CPU time, shielding effects – requiring more intensive computations – are precomputed, while acoustical sources derived from semi-empirical models are supplied in “real time”, as a function of the aircraft configuration.

In the present simulation, the diffraction effect of the aircraft geometry has been computed with the BEM which provides noise reduction delta SPLs at each one-third octave band from 20 Hz to 2 kHz. This latter frequency corresponds to the maximum frequency that the utilized CPUs resources can afford, given that the BEM computational cost increases with the square of frequency. For the one-third octave band from 2.5 to 12.5 kHz, the delta SPLs are extrapolated from the four last computed frequencies. Fan noise is assumed to be a point source located at point A in Figure 2 whereas jet noise is a source located at point B. In addition, delta SPLs are interpolated at the fan tones frequency for their diffraction computation. As for the fan tones, a specific treatment is made in CARMEN for the buzz saw noise. In the literature, it is done on a one-third octave band basis²⁰. In CARMEN, the tonal character is re-introduced and, for each one-third octave band, the calculated power is equally distributed among all the tones included in the considered one-third octave band to better model the physics and aid in any future auralization of the noise prediction. This quite rough assumption of equal power distribution leads to step-like tone amplitudes in the CARMEN spectra (see Figure 6).

IV. Results Comparison and Analysis

A. Comparison approach

A general survey of the shielding calculations made by the three organizations is first presented (§IV.B). Then, the comparisons of simulations #3-4 (see Table 1) are examined. The noise spectra computed at the source (before propagation to the ground) for each individual noise source on the V-2 aircraft are compared (§IV.C). These sources include the landing gear, fan, jet and the leading and trailing edges of the wings and tail. The noise spectra are computed for two operating conditions (takeoff and approach) at three representative polar directivity angles. In

general, fan noise is comprised of specific mechanisms that can be separated into broadband and tonal contributions. Different mechanisms are dominating the forward and aft noise emissions and these are furthermore highly dependent on the fan operating conditions. Consequently, for the simulation performed here, fan noise has to be assessed for different emission directions and operating conditions. Within this study, fan noise is separated in forward and aft fan with both broadband contribution and tonal contribution. The latter is shown with green points in Figure 5 and Figure 6, but with a different representation according to the three tools: in ANOPP, the tones are plotted in the one-third octave band center frequency whereas it is shown at discrete frequencies for CARMEN and PANAM. As detailed in §III.C, CARMEN buzz saw noise treatment in discrete frequencies leads to a different representation of these tones. Furthermore, to address the impact of noise shielding, the predicted engine shielding maps for the emission are evaluated (§IV.B).

In a second step, comparisons of simulations #7-8 are made of the noise level time histories computed for observers on the ground (§IV.D). Simple flight procedures with the same constant engine operating conditions used in §IV.C are used to simulate approach and departure. In this way, direct comparisons can be made between the noise at the source and on the ground, i.e., evaluating the implications of moving sound sources and sound propagation through the atmosphere. Overhead and sideline observers are defined for each flight path under consideration (representative takeoff and approach). Thus, both observers will be subject to different noise impact due to the emission directivity of the shielded vehicle under consideration. More details about the definition of these flight paths and observers, which are the same for both the V-R and V-2 aircraft, are given in the companion paper⁵. For each observer and flight path, time level histories of A-weighted Sound Pressure Level (L_A) are presented for each source listed above, as well as for the total aircraft. Additionally, Sound Exposure Level (SEL) contours – corresponding respectively to a take-off and a landing – are reported (simulations #11-12). These results correspond to longer and more realistic flight path simulations. In contrast to the simplified and constant flight path evaluated to extract time level-histories, these more realistic flight simulations include operation of the landing gear and of the high-lift system, and show varying velocity, thrust, and altitude along both approach and departure. These results will compare the source and shielding models, including the azimuthal directivity not considered in the spectral results, as well as propagation models for all three organizations. Finally, V-2 aircraft results and V-R aircraft results – presented in the companion paper⁵ – are compared on similar flight paths and highlights the benefit of the V-2 configuration in terms of engine noise shielding.

B. Engine noise shielding maps at 1 kHz

Figure 4 presents the engine noise source shielding maps generated with the CARMEN, PANAM, and ANOPP shielding tools, and used as input for the aircraft noise calculations. These maps are presented as a function of the angles θ and ϕ according to the following conventions: $\theta = 0^\circ$ is the nose aircraft direction and $\theta = 180^\circ$ is the rear aircraft direction, $\phi = 0^\circ$ is the ground direction and $\phi = 90^\circ$ is the starboard side direction. The SPL contour levels correspond to the noise attenuation in dB at 1 kHz for a given set of both right and left engine source locations. The *aft* location (Figure 4, d-f) is common to all three tools and is defined as the jet bypass nozzle exit whereas the *inlet* location (Figure 4, a-c) is the fan center for CARMEN and PANAM, and the nacelle face for ANOPP. The source is distributed for ANOPP whereas it is a point source for CARMEN and PANAM. ANOPP and PANAM use a high-frequency acoustics method whereas CARMEN uses a boundary element method. The closest agreement between the three tools is found for the *aft* results (d-f) where the source location is common. The same source distributions are used for the fan and jet noise shielding maps, despite the fact that the jet is a distributed source. This assumption of a point source is consistent with the fidelity of analysis carried out in system noise predictions. In separate predictions not included here, results from the SHADOW tool showed little sensitivity at low frequency to the location of the jet source downstream of the engine. The V-2 has a long fuselage upstream of the engine; small changes in this length should not be expected to result in much of a change to the shielding map. While capturing the effects of a distributed jet source do not impact the predictions significantly for the present geometry, this may be important for other vehicles. Despite the different computations of the shielding and source distributions, ANOPP, CARMEN, and PANAM provide similar results, although the shielding contours generated for PANAM exhibit higher local extrema. The shielding maps for the inlet radiation display the same general pattern, but a significant discrepancy is observed in the shadow zone, particularly the most shielded area. This area is very sensitive to the diffraction calculation but, surprisingly, ANOPP and CARMEN show close results despite their use of different calculation methods. Looking at the sideline area ($|\phi| > 55^\circ$), more agreement between the three tools is found. The large shadow zone and the strong gradients in the PANAM data as depicted in Figure 4c can be reduced and smoothed out by applying distributed sources as depicted in Figure 3. However, the single source approach was chosen for the SHADOW prediction for consistency with the underlying design study² which resulted in development of the low-noise vehicle V-2

Figure 4. Shielding predictions from the shielding tools for engine noise sources emitted at 1 kHz.

C. Noise spectra at the source

1. Approach conditions

Figure 5 shows a comparison at three different polar angles under the flight path of the approach noise for each of the three tools. It is clear that airframe noise is dominant for all three tools, due in part to the low thrust at approach but also to the shielding of the engine sources by the airframe. Engine noise does not appear to be a significant contributor to the approach noise except at aft angles and high frequencies, where the ANOPP and CARMEN tools predict engine noise to be above the airframe noise, and the PANAM engine noise is on par with airframe noise. Peak levels for the engine and airframe noise are similar for each of the three tools, although the peak frequency of the airframe noise differs significantly. Leading edge noise is the dominant airframe source for most of the predictions at low and middle frequencies, while the main gear noise is important at high frequencies.

Relatively good agreement is seen between the peak levels of the main gear noise, as well as the levels and spectral shape above 1 kHz. This implies that the gear noise due to the smaller details of the landing gear is being modeled in a similar fashion in each of the three tools. At lower frequencies, while the CARMEN and PANAM predictions show excellent agreement, the ANOPP prediction deviates in both spectral shape and peak level. While the spectral shape differences are related to the respective modeling assumptions of each tool, the difference in peak

level for the ANOPP prediction could be partly related to the assumed values for the additional parameters of the tire width and strut diameter that were not needed for the DLR gear noise prediction model utilized in PANAM or CARMEN. All three tools show that the main gear levels are reduced as the polar angle increases.

As expected, the agreement in the CARMEN and PANAM main gear spectra also extends to the nose gear spectra. The nose gear peak levels for these two predictions are nominally 3 dB below the main gear spectral levels. The differences seen with the ANOPP prediction for the main gear also extend to the nose gear. Thus, the ANOPP prediction for the nose gear has a pronounced low frequency spectral peak, and is nominally 10 dB below the accompanying main gear noise prediction.

Prediction of the leading and trailing edge noise shows much more variance in peak levels between the three tools, with no two tools consistently predicting the same level at multiple angles. However, the peak frequency for trailing edge noise matches for all three tools. The leading edge peak frequency is also similar for ANOPP and PANAM.

For the fan noise, all three tools produce similar spectral shapes and peak frequencies for the shielded overhead observer. Peak levels are quite similar for the CARMEN and ANOPP predictions at all three angles as well as the PANAM prediction at 90°, while the PANAM prediction has lower peak levels at the forward and rear angles. The tonal fan noise has a similar character for each of the three prediction tools, although the roll-off of the fan noise harmonics is softer for the ANOPP and CARMEN predictions than for the PANAM prediction.

The jet noise prediction for the approach case was only carried out for the PANAM and ANOPP simulations, as it is assumed insignificant in the CARMEN simulation. The PANAM and ANOPP jet noise predictions are seen to be quite similar, although the SPL levels predicted by ANOPP in the low frequency range are higher, particularly towards the aft angles, i.e. at 135°.

Figure 5. Source spectra at the approach condition for 60, 90 and 135 degrees relative to the flight direction.

2. Departure conditions

Figure 6 shows a comparison of the results obtained with each aircraft noise prediction tool for the same directivity angles when the aircraft is in the departure configuration. The leading edge device and gear are stowed. The only source of airframe noise comes from the clean wing trailing edge noise, which is plotted for the PANAM and ANOPP predictions. In general, a good agreement is found in the value of the peak frequency although the peak level and spectral shape obtained with the two prediction methods differ. The trailing edge noise makes a strong contribution to the overall aircraft noise only for the forward angle. The ANOPP trailing edge prediction also shows a much stronger directivity dependence than that predicted with PANAM or in the approach case (although the Mach number has not changed significantly between cases). This is believed to be related to including both flap side edge noise and clean trailing edge noise in the prediction for the approach case, while the departure case only has contributions from the clean wing trailing edge noise of the wing and tailplane. For the engine, it is clear that the jet noise is dominant at low frequencies, while the fan is important at high frequencies.

Agreement in the peak spectral level for the fan broadband noise is closest in the ANOPP and CARMEN predictions, particularly at 60°, where the PANAM prediction exhibits a very strong shielding of the fan source noise (cf. Figure 4c). The tonal richness of the fan spectrum is also quite different for each of the three prediction methods, although the overall spectral shape of the relative tonal amplitudes is similar for the ANOPP and CARMEN predictions. Figure 7 and Figure 8 show a more detailed comparison of jet noise and broadband fan noise, respectively, predicted for departure conditions with each of the three tools. It is clear that the aircraft offers significantly stronger shielding to the forward arc than to the rear. In agreement with the shielding maps in Figure 4 (§IV.B), PANAM predicts a stronger attenuation of the fan noise at 60°, while shielding prediction from the three tools are in close agreement for the jet noise. Overall, the best agreement between the three tools is found at 90°. However, it has to be noted that this emission angle is not subject to any moving source effects such as convective amplification or Doppler frequency shift.

Figure 6. Source spectra at the departure condition for 60, 90 and 135 degrees relative to the flight direction

Figure 7. Comparison of the fan broadband contribution at the departure condition at 60, 90 and 135 degrees.

Figure 8. Comparison of the jet contribution at the departure condition at 60, 90 and 135 degrees.

D. Time level histories

1. Approach

Figure 9 shows the time level history predicted with each of the three tools at the overhead and sideline observers for the simplified, fixed operating approach condition. The levels, as received on the ground, are A-weighted, which significantly reduces any low frequency content of the signal. The overall aircraft time level history is largely driven by the airframe noise for the overhead observer, except for the ANOPP prediction when the aircraft is far away and approaching during the first 15 seconds of the simulation. This behavior is due to the distinctive double hump in the prediction of the ANOPP engine time level history where there is minimal engine shielding at very low forward angles. It is to be related to the discrepancies observed on the shielding maps (Figure 4) around these angles, i.e. $\theta < 30^\circ$. However, the predicted shielded engine levels are much more similar at aft angles.

The agreement in the peak level of the main gear noise between all three methods is quite good and likely stems from the agreement previously observed with all three methods above 1 kHz, along with the application of A-weighting. Conversely, comparison of the ANOPP leading edge noise to the CARMEN and PANAM predictions can be explained by variations in the mid to high frequency spectral content. The difference in the time level history due to the lower peak levels observed in the ANOPP prediction are exacerbated by the fact that the leading edge noise predicted by ANOPP peaks at a lower frequency than in the PANAM prediction and even more so in the CARMEN prediction.

The time level history of the trailing edge noise for CARMEN exhibits a much sharper decay as the aircraft recedes than in the ANOPP and PANAM predictions. This cannot be attributed to the simulation of the sound propagation or ground effect, as identical propagation models are implemented and no ground effect is applied. Therefore, this effect is most likely related to the changes in directivity seen between Figure 5e and Figure 5h for

this noise component. Thus, while the overhead observer is primarily exposed to airframe noise, the sideline observer sees significant noise from the engine for all three prediction tools. The peak levels are in slightly better agreement than for the overhead observer and differ by only 1-2 dB(A). This can be related to the better agreement found in sideline direction on the shielding map previously presented in Figure 4.

Figure 10 highlights the overall engine and airframe time level histories obtained with each of the three methods at both observer points. The overall character of the time histories generated for both the engine and airframe components is similar with all three tools, with the exception of the behavior of the ANOPP engine noise, due to the lack of significant shielding early in the flyover noted previously. However, these differences are less pronounced for the sideline observer.

2. *Departure*

Figure 11 shows the time level history for the departure conditions at the overhead and sideline observers. The fan and jet contributions to the total aircraft noise are nearly equivalent for all cases shown. A more detailed comparison focusing on broadband fan and jet noise is presented in Figure 12. Early in the flyover, differences in the shielding of far forward angles in the ANOPP prediction is clear, particularly at the overhead observer. When the aircraft is moving away from the overhead observer, ANOPP jet noise is higher and this could be related to less shielding effect toward the very forward angles ($\theta > 145^\circ$) predicted by ANOPP (cf. Figure 4d-f). CARMEN and PANAM generally show close predictions.

3. *Comparison with reference aircraft V-R*

Figure 13 and Figure 14 compare the time level histories of the V-R aircraft with the present V-2 aircraft along the simplified trajectories (simulations #5-8). For both approach and departure, the benefit of the V-2 engine noise shielding is obvious on the overhead observers whereas it has a much lower relevancy on the sideline observer. Looking at the V-R aircraft predictions, the discrepancies between the three tools are lower than 4 dB(A). On the other hand, significant discrepancies are found for the V-2 predictions when the aircraft is moving closer to the observers and away from the overhead observer. This trend highlights the importance of the shielding calculation in aircraft noise predictions for configurations with significant shielding such as the V-2 aircraft.

E. SEL contours

Figure 15 compares the SEL contours predicted by the three tools for landing and take-off. In contrast to the results of §IV.B to §IV.D, the noise is now predicted for varying operating conditions as experienced along realistic flight trajectories. In landing, although there is a close agreement between the results obtained with the three tools for the highest SEL contour (80 dB(A)), the ANOPP and CARMEN results are in better agreement overall. The main discrepancy of the PANAM prediction lies in the area of X abscissa from -30 km to -20 km. This can directly be attributed to the increased airframe noise contribution as predicted by PANAM (Figure 13). In take-off, there is still a close agreement between the three tools for the 80 dB(A) contour but the 70 dB(A) contour immediately show significant discrepancies. Whereas CARMEN and PANAM show the same noise reduction along centerline ($Y = 0$), the contour lines show different patterns on either side towards the $X > 0$ direction. This discrepancy is repeated on the 60 dB(A) contour. The two lobes predicted by CARMEN and PANAM was related to the source point assumption, whereas the use of distributed sources in ANOPP leads to only one lobe in the contour. This was confirmed by comparison of DLR results shown here with a separate prediction (not included) using distributed sources.

Figure 9. Time level history of noise source contribution at approach condition on overhead observer (a-c) and sideline observer (d-f).

a. Overhead

b. Sideline

Figure 10. Comparison of the engine noise and airframe noise predictions respectively at approach conditions.

Figure 11. Time level history of noise source contribution at departure condition on overhead observer (a-c) and sideline observer (d-f).

a. Jet noise, overhead

b. Fan noise, overhead

c. Jet noise, sideline

d. Fan noise, sideline

Figure 12. Comparison of the jet noise and fan noise predictions respectively at departure conditions.

a. Overhead observer

b. Sideline observer

Figure 13. Comparison of the V-R (unshielded configuration) and V-2 engine noise predictions at approach condition.

a. Overhead observer

b. Sideline observer

Figure 14. Comparison of the V-R (unshielded configuration) and V-2 engine noise predictions at departure condition.

a. Landing

b. Take-off

Figure 15. SEL contours for the V-2 configuration.

V. Conclusion

The V-2 transport aircraft concept was created by DLR as an advanced configuration with noise reduction potential from shielding. It is a well defined model of a configuration with engines installed above the fuselage and high wing. The vehicle is the most promising low-noise configuration from a large DLR design study² in 2013. The design objective was a reduction of the dominant forward fan noise source along approach and departure. This concept was simulated for community noise conditions by the aircraft noise prediction tools of DLR, ONERA and NASA. A key prediction challenge was to include the effect of significant shielding of engine noise sources by the airframe as compared to the V-R concept where the engines are mounted conventionally under the wing. The simulation of the V-R was also predicted by all three organizations and reported in a companion paper.

All three prediction tools were used to compute the major noise reduction benefit of the V-2 as compared to the conventional V-R. As expected, the predicted noise reduction for the V-2 is greatest directly underneath the flight path and at the forward angles. Compared to the V-R aircraft, the V-2 can produce reductions as high as 10 to 20 dB along the flight track for both approach and departure. The three organizations have developed and implemented different prediction methodologies for shielding. The three shielding predictions generally agreed best directly under the aircraft with increasing differences at the far forward and far aft angles. At the aircraft level, agreement in the predicted noise was found to be generally improved where the effect of differences in the predicted shielding levels was less important. This trend can be seen in comparisons of both the single point observers and ground contours, and highlights the importance of the shielding calculation on the prediction of aircraft system level noise.

All three prediction methods also show good agreement in the predicted peak aircraft system noise level, typically within 3-4 dB, for both approach and departure. However, increasing differences, approaching 5-10 dB, could be observed at the far forward and aft angles. These larger differences between the three predictions are believed to be mostly due differences in the shielding predictions. Differences in the prediction of some component source levels were also observed, primarily for airframe noise sources. This was also identified and discussed in the companion paper. For the V-2, generally good agreement was found in the overall shape of the ground isocontours (although some noticeable differences in the overall size of the isocontours could be observed). These differences can be expected because the isocontours are very sensitive to even small quantitative differences in source noise levels. Separate from the engine noise shielding effects, the differences in levels for the airframe noise predictions of the three tools also influences the size of the ground contours for the approach condition.

Overall, the present study again highlights the shielding benefit that unconventional aircraft configurations can offer. While the results of all three tools show overall agreement in trends and levels, differences at a more detailed level of analysis also point to the challenge of predicting shielding, even for this relatively focused case. The shielding prediction challenges will also increase with the inclusion of flow effects, control surface deflection and, detailed geometry. Furthermore, prediction of acoustic liner attenuation and of an array of advanced technologies that were not included in this initial benchmark will continue to add to demands on the fidelity and validation of system noise prediction for low noise unconventional aircraft.

Acknowledgments

The funding for the DLR work package was partially supported by the Projektfoerderung zur Internationalen Zusammenarbeit and the DLR Directorate Aeronautics. The NASA contribution to the ANSWr collaboration is funded by the Aircraft Noise Reduction Subproject of the Advanced Air Transport Technology Project. Yueping Guo and Stuart Pope are thanked for their contribution to the NASA shielding prediction using the PAASSyN method. The ONERA contribution to the ANSWr collaboration is funded by internal budget dedicated to international collaborations. Furthermore, the authors would like to thank Mrs. Casey Burley for her valuable contribution to initiate and setup the ANSWr benchmark test.

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